Chapter 8

Rehabilitation Effectiveness

8.1 Introduction

A key objective of the pilot project effort was to measure and evaluate the effectiveness of sewer system rehabilitation. Rainfall and flow data from each pilot and control basin were used to determine if rehabilitation improvements resulted in reduced I/I. For comparison purposes, information was collected both before rehabilitation improvements (pre-rehabilitation) and after construction (post-rehabilitation). The data also provided a basis for modeling analysis to quantify pre-rehabilitation I/I, post-rehabilitation I/I, and I/I reduction.

Required tasks for estimating I/I reduction and determining rehabilitation effectiveness were:

- Defining the pilot basin (see Chapter 5)
- Monitoring flow (pre- and post-rehabilitation)
- Monitoring rainfall
- Modeling flow (pre- and post-rehabilitation)

8.2 Pilot Project Basins

As described in Chapter 5, the pilot projects consisted of both pilot basins and control basins. The basin where the rehabilitation work was actually performed was defined as the pilot basin; the pilot basin could encompass either part of or all the mini-basin.

Control basins were established in the vicinity of the pilot basins and were monitored simultaneously. The purpose of establishing control basins was to provide a flow record in a nearby basin in which there was no I/I rehabilitation effort. The change in flow response of the pilot basin between the pre-rehabilitation and post-rehabilitation monitoring seasons could be compared with the change in flow response of a basin without I/I reduction.

To evaluate I/I reduction separately from the modeling analysis, the measured flows from the control basins were compared with the measured flows collected from the pilot basins during both the pre- and post-rehabilitation periods.

8.3 Flow Monitoring

The pilot projects were conducted as part of a larger regional infiltration and inflow program, as described in Chapter 1. In support of the regional program, over 775 flow meters were placed throughout the King County service area during the 2000/2001 and 2001/2002 wet seasons. Documentation for the flow monitoring conducted during these two periods is provided in the following:

- *2000/2001 Wet Weather Flow Monitoring, May 2001*
- *2001/2002 Wet Weather Flow Monitoring, June 2002*

8.3.1 Pilot Project Flow Monitoring Periods

8.3.1.1 Pre-Rehabilitation Flow Monitoring

For the pilot projects in which the pilot basin boundary was the same as the mini-basin boundary, flow data collected in 2000/2001 and 2001/2002 was considered sufficient to establish existing, or pre-rehabilitation conditions. These projects included Lake Forest Park, Ronald, and the Manhole Projects (Coal Creek, Northshore, and Val Vue).

Additional flow monitoring was needed to measure pre-rehabilitation conditions where pilot basins and control basins were smaller than the original mini-basin. These projects included Auburn, Brier, Kent, Kirkland, Mercer Island, Redmond, and Skyway. The additional pre-rehabilitation flow monitoring took place from November 1, 2002 to January 15, 2003. Pilot basin boundaries and flow meter locations are presented in Chapter 5, Figures 5-2 to 5-13. A summary of the 2002/2003 pre-rehabilitation monitoring is presented in Appendix D.

8.3.1.2 Post-Rehabilitation Flow Monitoring

Post-rehabilitation flow monitoring was conducted for all the pilot and control basins associated with the pilot projects. For pilot basins, flow monitoring was conducted to assist in evaluating the effectiveness of rehabilitation. For control basins, post-rehabilitation flow monitoring was conducted to provide comparison to pre-rehabilitation flow data in a basin with no I/I reduction.

The proposed period for post-rehabilitation flow monitoring was November 1, 2003 to January 15, 2004. However, the actual initiation of flow monitoring in each basin depended on completion of rehabilitation improvements. In some cases, post-rehabilitation flow monitoring began before the November 1 target date; in other cases, it began after November 1. Table 8-1 presents the start and end of flow monitoring data used to estimate I/I reduction for all monitoring periods at all sites.

Table 8-1. Flow Monitoring Duration Summary

Basin Name	Flow Meter Name	Pre-Rehabilitation Monitoring			Post-Rehabilitation Monitoring
		2000-2001	2001-2002	2002-2003	2003-2004
Auburn Pilot A	Auburn Pilot			11/4/02–4/24/03	10/27/03–2/4/04
Auburn Pilot B	Auburn Control	11/1/00–1/15/01	11/1/01–1/15/02	11/4/02–4/23/03	10/8/03–2/4/04
See Note	Auburn Subtraction	11/1/00–1/15/01	11/1/01–1/15/02	11/4/02–5/1/03	10/27/03–2/4/04
Brier Control	Brier Control			11/5/02–6/1/03	12/1/03–2/6/04
Brier Pilot	Brier Pilot	11/1/00–1/15/01	11/1/01–1/15/02	11/5/02–5/30/03	12/16/03–2/6/04
Coal Creek Control	Coal Creek Control	11/1/00–1/15/01	11/1/01–1/15/02		10/31/03–2/4/04
Coal Creek Pilot	Coal Creek Pilot	11/1/00–1/15/01	11/1/01–1/15/02		12/15/03–2/4/04
Kent Control	Kent Control			10/31/02–5/27/03	10/9/03–3/8/04
Kent Pilot A and B	Kent Pilot A and B			10/31/02–5/27/03	1/16/04–3/8/04
Kent Mini	Kent Mini	11/1/00–1/15/01	11/1/01–1/15/02		
Kirkland Control	Kirkland Control			11/5/02–6/17/03	10/7/03–2/4/04
Kirkland Pilot	Kirkland Mini	11/1/00–1/15/01	11/1/01–1/15/02	11/6/02–7/13/03	10/9/03–2/4/04
Lake Forest Park Control	Lake Forest Park Control	11/1/00–1/15/01	11/1/01–1/15/02		11/3/03–2/6/04
Lake Forest Park Pilot	Lake Forest Park Pilot	11/1/00–1/15/01	11/1/01–1/15/02		11/5/03–2/6/04
Mercer Control	Mercer Control			11/1/02–7/21/03	10/7/03–2/4/04
Mercer Island Pilot	Mercer Mini	11/1/00–1/15/01	11/1/01–1/15/02	3/5/03–4/20/03	10/21/03–2/4/04
Northshore Control	Northshore Control	11/1/00–1/15/01	11/1/01–1/15/02		10/31/03–2/6/04
Northshore Pilot	Northshore Pilot	11/1/00–1/15/01	11/1/01–1/15/02		12/15/03–2/6/04
Redmond Control	Redmond Control			11/1/02–7/22/03	11/21/03–3/2/04
Redmond Pilot A	Redmond Pilot			11/1/02–7/22/03	12/1/03–3/8/04
Redmond Pilot B	Redmond Mini	11/1/00–1/15/01	11/1/01–1/15/02	12/12/02–6/1/03	10/21/03–3/2/04
Ronald Control	Ronald Control	11/1/00–1/15/01	11/1/01–1/15/02		10/31/03–2/26/04
Ronald Pilot	Ronald Pilot	11/1/00–1/15/01	11/1/01–1/15/02		10/22/03–2/26/04
Skyway Control	Skyway Control			10/29/02–5/2/03	10/6/03–2/2/04
Skyway Pilot	Skyway Pilot			10/29/02–5/2/03	10/9/03–2/2/04
Skyway Mini	Skyway Mini	11/1/00–1/15/01	11/1/01–1/15/02		11/20/03–2/2/04
Val Vue Control	Val Vue Control	11/1/00–1/15/01	11/1/01–1/15/02		10/31/03–2/17/04
Val Vue Pilot	Val Vue Pilot	11/1/00–1/15/01	11/1/01–1/15/02		10/22/03–2/17/04

Note: The Auburn subtraction meter measured flows from an upstream basin that was subtracted from the Auburn pilot meter to establish flows in the Auburn pilot A basin.

Flow monitoring continued beyond the proposed January 15, 2004 completion date to collect measured flows during additional wet weather events. For the purpose of determining I/I reduction, measured flows were collected until the beginning of February 2004. The last significant storm during this period occurred January 29, 2004.

8.3.1.3 Field Verification

Field verifications (site calibrations) were performed during flow meter installation and throughout the duration of the project. Performing site calibrations was important for verifying that each flow meter accurately measured flows. Field verification consisted of manually measuring flow velocity and depth and comparing these numbers to meter readings.

During the 2002/2003 and 2003/2004 monitoring periods, King County field personnel entered the manhole at each site and confirmed velocity using a portable velocity meter. Depth was confirmed using a ruler with 1/8th-inch increments.

At five sites monitored both in 2002/2003 and 2003/2004, a calibrated weir was used to verify flow instead of the portable velocity meter. The weir was used in locations where the flow was considered too low to conduct a site calibration using a hand-held velocity meter.

Detailed documentation regarding the frequency and results of site calibrations is provided in Appendix D.

8.3.2 Flow Monitoring Data Processing

Raw data collected by flow meters underwent several processes to achieve the status of "final" data. This series of steps was necessary to develop confidence and reliability in the measured flow data. Final data were used to quantify dry weather flow and I/I. Final data were also used for model calibration.

8.3.2.1 Data Review

Data review, that is, the process of evaluating depth and velocity readings recorded by the flow meter, was conducted by field crews during weekly data collections and by the analyst as processing continued during monitoring. Data collection involved downloading information from the flow meter to a laptop computer. Field crews reviewed the data to ensure that flow meter sensors were operating correctly and to look for invalid data resulting from sensors affected by debris. Invalid depth or velocity readings can be recorded when the depth or velocity sensors require cleaning, or if a sensor has failed and requires replacement. Debris such as rags, paper, and grease can build up on sensors during normal operation and if the sewer experiences surcharging.

8.3.2.2 Data Editing and Finalization

If the flow meter sensor equipment becomes fouled, the data collected is not a valid representation of the depth and/or velocity of flows at the site. For this reason, the data was edited to ensure that only valid data was used in sequential quantity and I/I calculations. (Note that raw data with invalid depth and velocity readings were preserved to allow subsequent evaluation of the data review and editing process.) Invalid velocity data can often be "reconstituted." Velocity reconstitution is discussed in Appendix D.

Data editing is the process of identifying invalid data or applying modifications to correct inaccurate raw data. Corrections to raw data were performed only when justified with additional field information. A data analyst evaluated field verification data by plotting it in conjunction with a scatter plot of the flow meter data. The field verification points that fell within the scatter plot confirmed that the flow meter sensors and field verifications were consistent and no further velocity or depth adjustments were required. If field verification points fell outside the scatter plot, they could be used to adjust the depth and/or velocity data.

In some cases, the raw data was determined to be invalid; however, there was insufficient information to correct the raw data. In these cases, the invalid data was excluded from the final data. See Appendix D for additional information.

The method by which invalid data was documented depended on the type of flow meter equipment and the capability of the software available for data editing. Three types of flow meters were used, and the associated software varied. With some types of flow meter software, it was possible to attach a descriptive identifier ("flag") to each record. The flag could be used to retain the data record (date, time, and entity value) in the database, but exclude invalid data from the final flow quantities. For other types of software, it was necessary to delete the invalid data from the final flow so it was not included in the final flow calculation. For quality assurance/quality control (QA/QC) and/or auditing purposes, the raw flow data was retained for comparison with the final flow data.

8.3.3 Flow Monitoring Data Issues

During the 2002-2003 flow-monitoring period, the "uptime percent" was an average of 94 percent. The uptime percent is defined as the percentage of total data points recorded by a flow meter and considered valid. When uptime was less than 100 percent, some of the collected information was considered invalid; this part of the data was not used for quantity or I/I calculations.

At nine sites, data uptime was 100 percent. At the nine other sites, there were data losses ranging in duration from 3 days to a little over 3 weeks. At seven of these sites, the uptime percent was still at or above 92 percent, even with the data loss time taken into consideration. At the sites with the most significant data gaps (Redmond Pilot and Brier Control), the uptime percent was approximately 70 percent and 82 percent, respectively.

In an effort to diagnose and minimize data loss during the 2002/2003 pre-rehabilitation flow monitoring period, King County staff and the monitoring equipment vendor investigated possible reasons for the data loss. Data loss appeared to be caused by three factors:

1. Mismatches in computer software versions between the flow meter and the laptop computer used to download the data
2. Low battery voltages
3. Meter "lock up" (that is, when the meter fails to record data) during field verification

The first two concerns were easily corrected. Mismatches in computer software were corrected by ensuring that necessary updates were synchronized and completed. Low battery voltages were corrected by changing batteries either every 2 weeks or whenever the battery voltage dropped below 10 volts.

It was determined that meter "lock up" was a function of field installation and maintenance. Correcting meter lock up during field verification required adjustment of the protocol used for conducting field verifications. If lock up occurred after the field crew left the site without re-activating the meter (resending site setup data to the meter), data loss took place between the site visit and the next data download. This issue was addressed by re-activating after each download and field verification.

During the post-rehabilitation period, the uptime percentage improved in comparison to the pre-rehabilitation period. For the 28 sites monitored and for an average of 100 collection days, the uptime was 97 percent. As indicated by the improved uptime percent during post-rehabilitation flow monitoring, the corrective measures appeared to be successful. Data losses during the post-rehabilitation period ranged from 1 day to about 1 week at nine sites. The data losses during post-rehabilitation monitoring resulted primarily from meter malfunction.

8.4 Rainfall Monitoring

Rainfall in each pilot and control basin was quantified using two methods:

- Rainfall was measured using a county-wide rain gauge network
- Rainfall was estimated using radar technology and rain gauge data

The primary purpose for quantifying rainfall in each pilot and control basin was to develop input for flow modeling (see Section 8.5).

8.4.1 Rainfall Time Series

A rainfall time series is a record of rainfall over a long period of time. Rain gauge data from the City of Seattle and from the County's Water and Land Resources Division and Wastewater Treatment Division were combined into one representative rainfall time series for each pilot and control basin.

The centroid (area center) of the basin was chosen as the point-of-reference for distance estimates to the three closest rain gauges that triangulated each basin (Figure 8-1). In cases where the three closest gauges were missing significant amounts of data, the next closest gauge was also added to the combination. Gauges collected data every 5 minutes. Gauges that did not work properly during any given period were excluded from the analysis altogether. See Appendix E for a list of the gauges used for each pilot and control basin, and for a list of the gauges near the pilot and control basins that were excluded due to data quality concerns.

Rainfall time series were generated for each project basin using an inverse distance-weighted interpolation scheme. The interpolation scheme was based on the assumption that gauges further from a modeling basin reflect the basin rainfall less than closer gauges. The weighting power (exponent that determines how mathematically dependent the final interpolated value is on the distance between the gauge and the basin centroid) was set to the square. Other weighting powers were considered; however, the square is assumed among the scientific community to be an optimal standard.

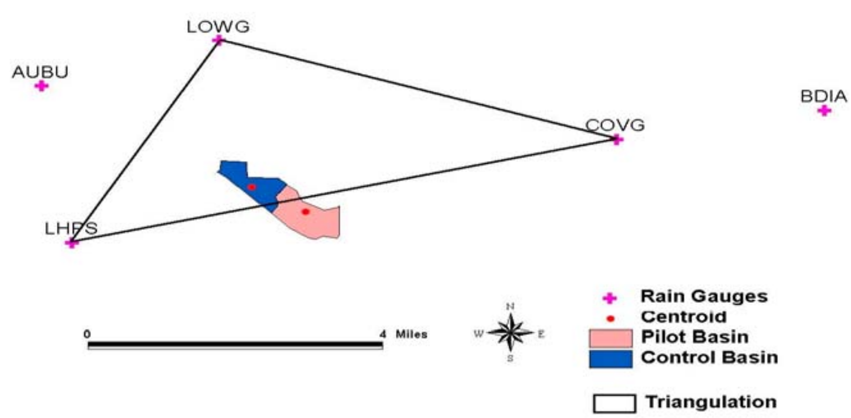


Figure 8-1. Rainfall Gauge Triangulation

8.4.2 CALAMAR Time Series

CALAMAR (calcul de lames d'eau a l'aide du radar, which translates as "Calculating Rain with the Aid of Radar") was used to calculate rainfall during all storm events corresponding to the flow monitoring periods. (Note that CALAMAR was not developed for the 2000-2001 flow-monitoring period. See Appendix E for additional detail.)

CALAMAR is based on comparing rain gauge values to radar reflectivity at multiple locations, and statistically calibrating the radar reflectivity over a calibration zone. The CALAMAR process allows a finer resolution in geographic coverage than would be obtainable with rain gauges alone. Reflectivity images are acquired from the National Weather Service NEXRAD radar system and processed into rainfall over pixels with geographic resolution of 1 square kilometer (km^2) (per pixel) and a temporal resolution of 5 minutes. To ensure calibration efficiency, eight calibration zones (200 to 500 km^2 each) were set up for the King County service area.

The relationship between pixels and the basin area was defined using the Geographic Information System (GIS). CALAMAR was used to generate rainfall time series during moderate to heavy rainfall events only. The CALAMAR event time series was substituted into the averaged rain gauge time series to become a composite time series. See Appendix E for additional information on the CALAMAR technology and how CALAMAR was developed for this project.

8.5 Flow Modeling

This section provides the background, approach, and methodology pertaining to the development of models to simulate flows. Section 8.6 provides more information about how I/I reduction was identified and estimated for each pilot basin.

Flow modeling of the pilot and control basins was used to determine whether rehabilitation improvements resulted in reduced peak I/I. A modeling software package (MOUSE, or Modeling of Urban Sewers) developed by the Danish Hydraulic Institute (DHI) was used for continuous simulation of rainfall-dependent I/I and for quantifying the I/I entering the sewer system in each pilot and control basin. Pre-rehabilitation and post-rehabilitation simulation results were compared to identify I/I reduction. Reduction in the 20-year peak I/I was also estimated using the models developed for each pilot basin.

Using measured rainfall data as input, MOUSE Rainfall-Dependent Infiltration and Inflow (RDII) hydrologic models were calibrated to observed sewer flow response in each pilot and control basin. RDII is a MOUSE software module for continuous modeling of the runoff process. Calibration of the MOUSE hydrologic models to simulate flow response from each basin relied on matching measured flows; these flows were measured over the course of available wet seasons, depending on data availability. Note that this calibration approach differs from the more common approach of focusing only on matching flows during discrete wet weather events.

Utilizing all of the measured flow data in the calibration process allowed selection of well-tuned parameters to define infiltration flows, which are highly dependent on antecedent (ground moisture) conditions. A key factor influencing selection of this calibration approach is the fact that in King County, infiltration is commonly a significant component of I/I.

8.5.1 Modeling Overview and Background

Hydrologic models quantify the flow out of a basin in response to rainfall. The model simulates the hydrologic transformation of rainfall into the I/I that enters the sewer system in the basin.

The input needed for MOUSE hydrologic models is based on the characteristics of each basin, and is briefly described below:

- **Basin description:** Basin characteristics such as total area, slope, and impervious/pervious surface area
- **Base wastewater flow data:** A flow record during dry periods to assess base wastewater discharge from industrial/commercial/residential land use, and to establish base infiltration
- **Rainfall:** A continuous rainfall time series for a study area

The *hydrologic* model output is a series of hydrographs (graphs of flow versus time) for specified time periods at particular basin outlets. In turn, the hydrographs are inputs to a *hydraulic* model, which simulates routing the flows through a conveyance system. Figure 8-2 shows a typical exchange of data between the hydrologic and hydraulic models.

Note that hydraulic models convey flows generated by hydrologic models from one basin to another. The models are typically based on a conveyance system's physical characteristics, such as pipe length, pipe material, pipe slope, roughness coefficient, manhole geometry, and others. The extensive hydraulic capability available in MOUSE was not needed for the pilot project modeling because the sewer system was not simulated in detail. A simplified approach was adopted (see Section 8.5.2).

The hydrologic and hydraulic models are coupled together to represent and quantify how a system behaves with respect to I/I. Modeled I/I consists of multiple components (see Figure 8-3). During dry weather, only wastewater and a relatively constant amount of clear water, or infiltration flow, are present. During wet weather, there is usually a fast response almost immediately after rainfall begins; the response continues throughout the rainfall event. Typically, there is also a response that builds and decays more slowly in response to the rainfall event.

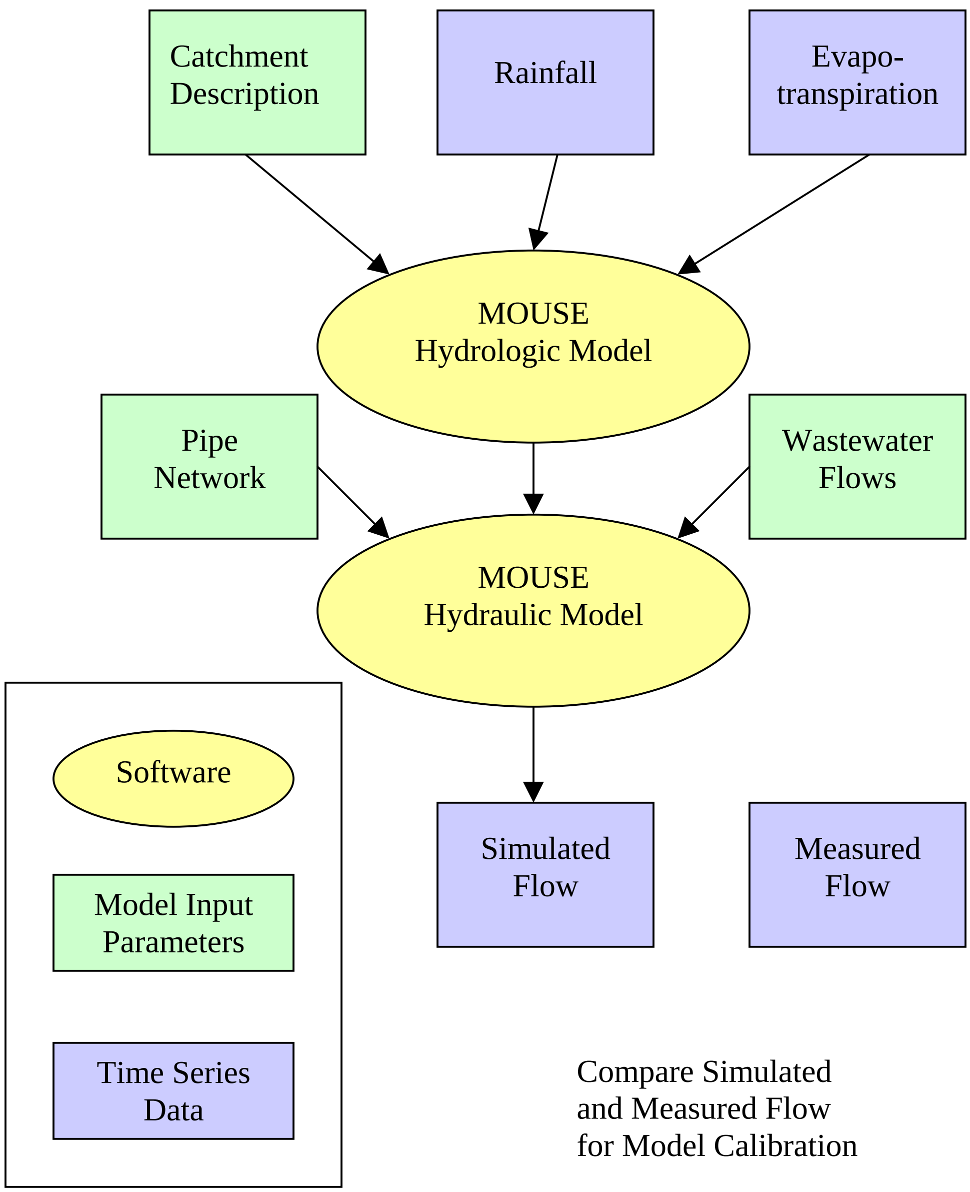
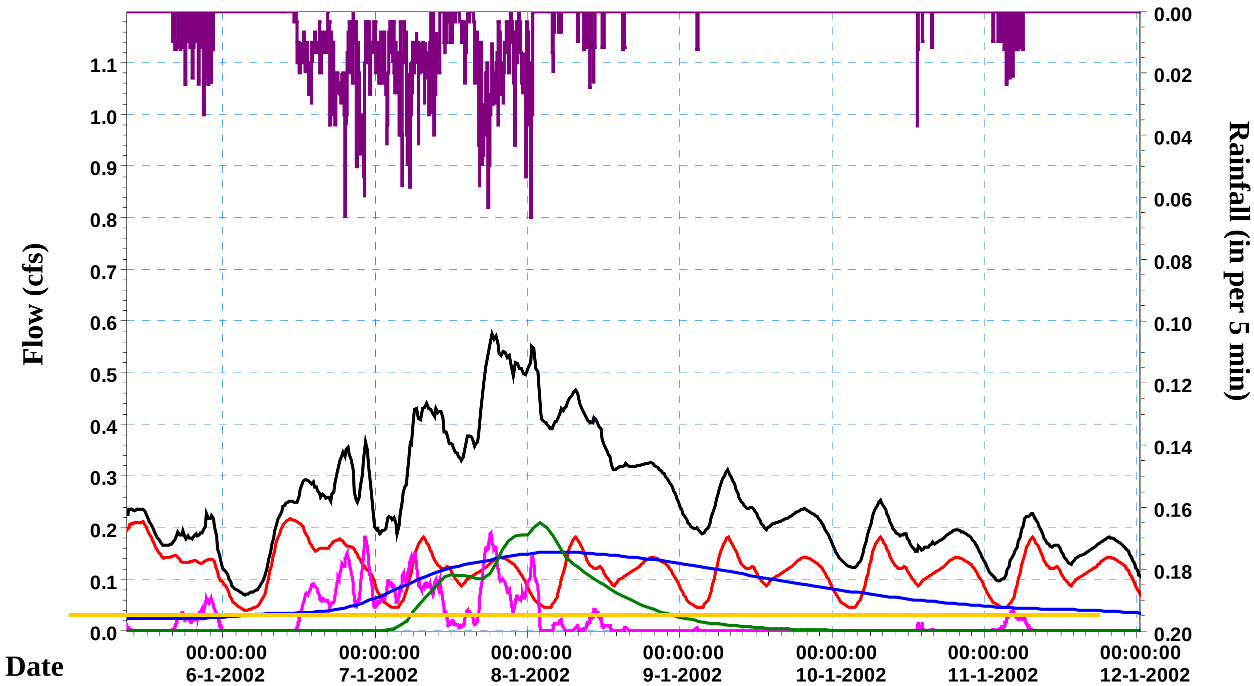


Figure 8-2. MOUSE Hydrologic and Hydraulic Model Components



Legend: Dry Weather Flow, Base Infiltration, Measured Rainfall, Date Format (dd-mm-yyyy), Total Simulated Flow, Fast Response Component, Slow Infiltration, Rapid Infiltration

Figure 8-3. Simulated Flow Components

These observations of real-world flow patterns provide a basis for establishing mathematical representations for each component of wastewater and I/I flow. The time series flow data for all types of wastewater and I/I flow can be added together to equal the total outlet flow for each basin. The following types of flows were used by the hydrologic models developed for the pilot projects:

- **Dry weather flow estimated from flow data:**
  - **Diurnal wastewater flow from homes and businesses:** This type of flow is the only component intended for conveyance by the sanitary sewer system. Its magnitude varies, usually in a daily diurnal pattern as part of the dry weather flow (the dry weather flow is shown in Figure 8-3).
  - **Base infiltration:** This type of infiltration is flow that continuously enters the sanitary sewer system, even during extended periods of dry weather. Because this flow does not correlate with rainfall, it is likely that it originates from permanent groundwater formations coincident with the sewer system. Base infiltration is assumed to remain generally constant with time and adds together with the diurnal wastewater flow to become dry weather flow.

- **Wet weather flow based on response to rainfall:**
  - **Fast response:** This type of flow represents a quick response to rainfall events within the basin. Fast response flow may consist of runoff from impervious areas. In a separated sewer system, this type of flow should not be in the wastewater stream. During large rain events, however, runoff from saturated pervious areas may also contribute to fast response. Within the modeling approach, the defining characteristic of fast response is that unlike infiltration flow, it is largely insensitive to antecedent conditions. Model A is the MOUSE module that is used to simulate fast response.
  - **Rapid infiltration:** This type of infiltration is the most rapid of the three infiltration flow components represented in the modeling approach. Rapid infiltration response is typically due to infiltration near infrastructure imperfections in which the ground becomes temporarily saturated. Rapid infiltration characteristically starts and ends with each rainfall event. Unlike fast response, the amount of rapid infiltration response may be larger due to antecedent rainfall or may be smaller due to a lack of antecedent rainfall. MOUSE RDII is the module used to simulate rapid and slow infiltration. Rapid infiltration is the overland flow component of MOUSE.
  - **Slow infiltration:** This type of infiltration is flow that responds more slowly to individual rainfall events. Slow infiltration is typically related to the rise and fall of groundwater in response to rainfall. Slow infiltration generally does not start until well after the start of the rainfall, and continues well past the end of it. Slow infiltration is the sum of "interflow" and "groundwater flow" in the MOUSE RDII module.

8.5.2 Modeling Approach

Models representative of the pilot and control basins were developed, with corresponding basin delineation and flow meter placement (see Figures 5-2 to 5-13). The models included the best available input information at the time of model development. The models were developed as follows:

- The model configuration was developed from an existing King County GIS database (see Section 8.5.2.1).
- Rainfall input was developed from a network of rainfall gauges and from CALAMAR (see Section 8.4.2).
- Evapo-transpiration (ET) input was developed from a Washington State University agricultural database that uses weather stations to calculate the required model input (see Section 8.5.2.3).

The models were calibrated to all available flow data by adjusting modeling parameters until modeled hydrographs qualitatively “fit” flow meter hydrographs for each basin. See Table 8-1 for a summary of collection dates for flow data from each basin. Section 8.5.3 presents additional detail regarding the calibration process.

8.5.2.1 Hydraulic Model Input

The hydrologic model basin parameters were developed from an existing King County GIS database. The parameters were based on the physical characteristics of each basin.

The hydraulic model conveyance parameters were developed to convey the flows from one basin to the next without backwater effects (flow constriction). The piping parameters were generically set for all basins and do not represent the true infrastructure. This is a standard modeling method at this scale. Only the hydrological components of the network of basins are of concern; the hydraulics of the network of piping within each basin is relatively unimportant. To maintain free-flow conditions, the piping was specified as smooth, circular concrete pipes with a 5-foot diameter and a 200-foot length. The connecting manholes were all designated as 5 feet in diameter, with a ground level of 30 feet and an invert (pipe bottom) that dropped 1 foot for every manhole as the layout progressed downstream.

8.5.2.2 Rainfall Input

Rainfall time series were developed for the pilot project basins as model input. The rainfall derived for each basin was used as input into the MOUSE model. As described in Section 8.5.1 and illustrated in Figure 8-2, rainfall time series feed the MOUSE continuous hydrologic process used to simulate flows from each basin.

As described in Section 8.4, the rainfall time series for each basin was developed as a composite of CALAMAR data and rain gauge data. Rain gauges were not specifically installed in each basin. Therefore, it was necessary to combine the data from multiple gauges located near each basin to estimate the rainfall that actually occurred within the basin boundary. Because the rainfall data were used for model input, complete data sets without gaps were required. In addition, to enhance the data collected from the rain gauges, CALAMAR was utilized to obtain better geographic coverage than would be obtainable with rain gauges alone. Because CALAMAR was only available for individual rainfall events, rain gauge data was still necessary to develop the rainfall time series for each basin encompassing the time prior to and during the pre-rehabilitation and post-rehabilitation periods.

8.5.2.3 Evapo-transpiration Input

An evapo-transpiration (ET) time series, used for all modeling basins, was developed as model input. The ET time series accounted for rainfall loss during rainfall events and enabled the model to “dry out” during non-rainfall time periods. The series was developed from weather station data obtained from the Washington State University Public Agricultural Weather System (PAWS) database. The Puyallup weather station was the closest to the King County service area where ET is measured. Data gaps were filled by the next closest weather station in Mount Vernon. The modeling effort used the Penman Grass reference ET values that were calculated from the weather station data at a 24-hour interval. Penman Grass ET is the daily reference crop ET from an extensive surface of 3-to-6 inches tall, green grass cover of uniform height which is actively growing, completely shading the ground, and not short of water.

8.5.3 Model Calibration

Calibration is used for nearly every kind of scientific modeling. Physically based models generally have some parameters that can be directly measured and others that cannot. During calibration, the values of non-measurable parameters are adjusted to satisfy the input/output relationship of the modeled system. This is accomplished by running the model using incremental iterations of values for one or more of the unknown parameters. For the pilot and control basins, model calibration entailed adjusting the model parameters that controlled the magnitude and shape of simulated I/I flows. The outputs from successive model iterations were compared with measured values for the output parameters (such as flow, for a hydrologic model). When the modeled output closely and consistently matched the measured output, the model was considered calibrated.

The procedure for selecting parameter values to calibrate each of the flow components is complex. It requires a detailed understanding of the relationship between parameter values defined in MOUSE and the resulting simulated flow response. The calibration procedure typically begins by first defining the less variable components of flow, such as dry weather flow. Therefore, the initial steps of calibration involve comparing and calibrating model simulations to records collected during periods of dry weather. After dry weather calibration is completed, the effort focuses on matching simulation results to recorded wet weather flows. In general, the procedure involves targeting particular periods of the observed flow record to first match hydrograph volume, then matching peak flow and shape.

8.5.3.1 Calibration Flow Time Series

MOUSE model “runs” (a run is defined as a single iteration of model calculations, representing a single parameter combination) were compared to the collected flow data. The flow data was collected at several monitoring sites and generally could be directly compared with the modeling results for each basin. However, the calibration process for some of the pilot and control basins was based upon the addition or subtraction of data between two or more different meters (see Table 8-2).

The subtractions and additions were completed by comparing upstream and downstream measured flow hydrographs. Flow travel time lags were corrected for as well as any other effects that might inhibit the subtraction. The final subtracted data was averaged over a 60-minute moving interval. Note that when calibration relied on addition or subtraction of data, the data was considered valid only for time periods when valid data was collected at all required meters.

Table 8-2. Calibration Flow Definition

Basin Name	Calibration Flow Basis	Calibration Flow Definition
Auburn Pilot A	Meter Subtraction	Auburn Pilot A minus Auburn Subtraction
Auburn Pilot B	Meter Subtraction	Auburn Pilot B minus Auburn Pilot A
Brier Control	Single Meter	Brier Control
Brier Pilot	Meter Subtraction	Brier Pilot minus Brier Control
Coal Creek Control	Single Meter	Coal Creek Control
Coal Creek Pilot	Single Meter	Coal Creek Pilot
Kent Control	Single Meter	Kent Control
Kent Pilot	Meter Addition	Kent Pilot A plus Kent Pilot B
Kirkland Control	Single Meter	Kirkland Control
Kirkland Pilot	Meter Subtraction	Kirkland Pilot minus Kirkland Control
Lake Forest Park Control	Single Meter	Lake Forest Control
Lake Forest Park Pilot	Single Meter	Lake Forest Pilot
Mercer Island Control	Single Meter	Mercer Island Control
Mercer Island Pilot	Meter Subtraction	Mercer Island Pilot minus Mercer Island Control
Northshore Control	Single Meter	Northshore Control
Northshore Pilot	Single Meter	Northshore Pilot
Redmond Control	Single Meter	Redmond Control
Redmond Pilot A	Single Meter	Redmond Pilot A
Redmond Pilot B	Meter Subtraction	Redmond Pilot B minus (Redmond Pilot A plus Redmond Control)
Ronald Control	Single Meter	Ronald Control
Ronald Pilot	Single Meter	Ronald Pilot
Skyway Control	Single Meter	Skyway Control
Skyway Pilot	Single Meter	Skyway Pilot
Val Vue Control	Single Meter	Val Vue Control
Val Vue Pilot	Single Meter	Val Vue Pilot

Note: Locations and relationships between meters are presented in Figures 5-2 to 5-13.

8.5.3.2 Dry Weather Calibration

The first step in the calibration process for each model basin was to match simulated flows with flows measured during dry weather. The dry weather flows measured at the beginning of each monitoring period were used to define and calibrate dry weather flow input into the model. Dry weather flows were represented in MOUSE using three components (see Figure 8-4 for additional detail):

1. The daily diurnal pattern above the daily minimum flow
2. The portion of the daily minimum flow estimated to be wastewater (the remaining flow below the daily minimum flow was assumed to be base infiltration)
3. The portion of the daily minimum flow estimated to be dry weather infiltration (base infiltration)

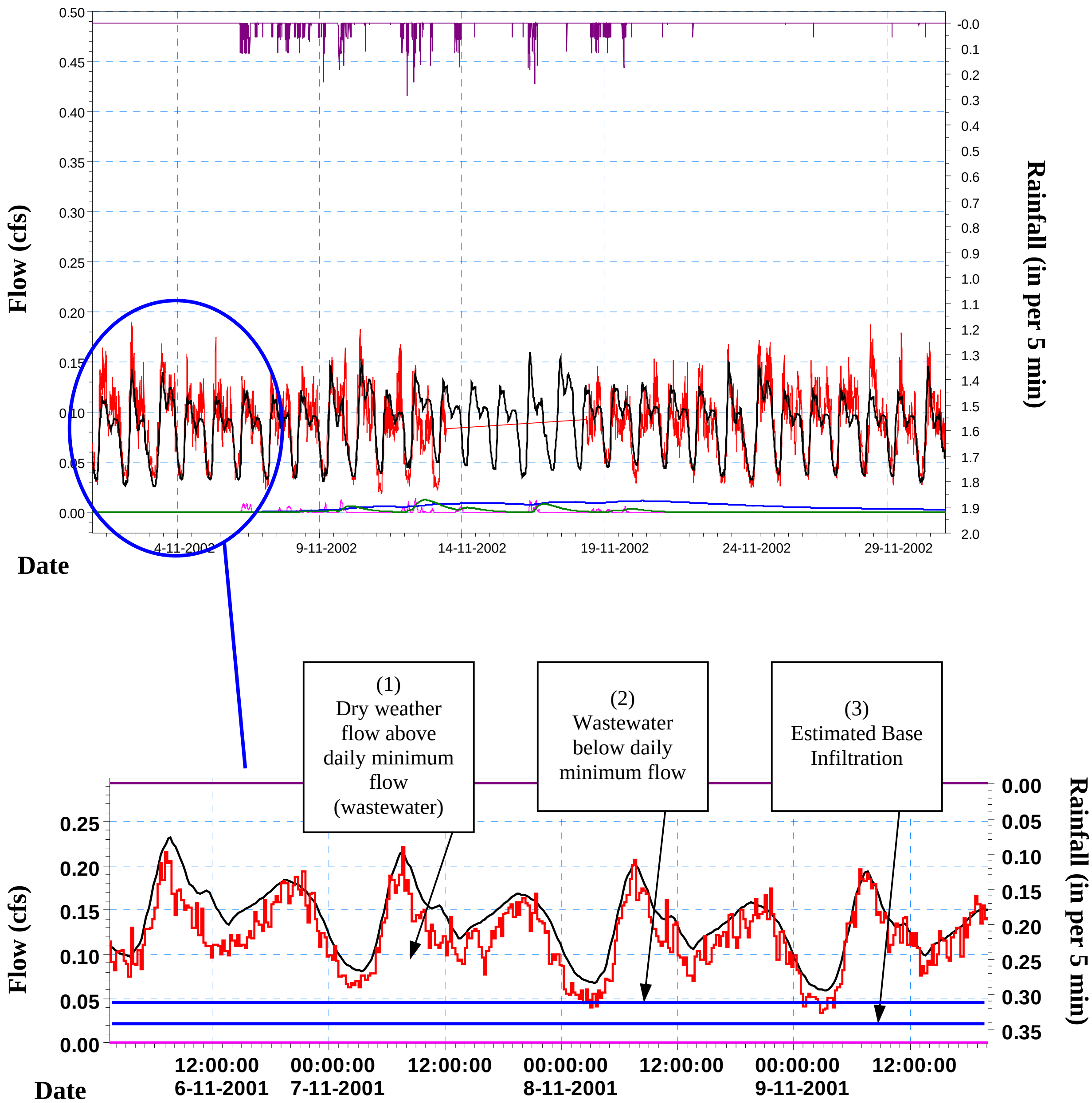


Figure 8-4. Dry Weather Flow Calibration

To calibrate each basin to existing conditions, the amount of dry weather flow was derived from the available measured flow data. Because monitoring data was available during dry periods, it was not necessary to use population to determine the wastewater contribution in each basin (population can provide an estimate of the wastewater contribution in the absence of flow data collected over dry periods).

8.5.3.3 Wet Weather Calibration

As explained in Section 8.5.1, MOUSE represents wet weather I/I as three distinct responses: fast response, rapid infiltration, and slow infiltration. During the calibration process, each wet weather flow component was “tuned” (partially calibrated) individually in order (from the slow infiltration response to the fast response). Then an overall final tuning was done.

Tuning for the slow infiltration response was done by matching the diurnal dry weather flow pattern to the flow data before and after storm events as well as at the end of the monitoring season. If the slow infiltration response component was adjusted correctly, the dry weather flow pattern matched the flow data at the higher flow around the storm events. This approach was a way of separating out the component into flows that were primarily dependent on the addition of the slow infiltration component.

Tuning for the rapid infiltration component was done by matching storm event volumes and shapes with special attention to matching the flow recession of the storm events. The rapid infiltration component was primarily responsible for the recession limb of the storm event. Measured flow responses to all storms were used for calibration; however, it was typically not possible to match simulated flows to measured flow responses for all storms. In these cases, more emphasis was placed on matching flow responses to large, rather than small storms.

The last component to be tuned was the fast response component. The fast response component was tuned to match storm peaks. With regard to shape and peak, this effort involved fine-tuning the rapid infiltration response. Large storms were matched at the cost of smaller storms when there were inconsistencies.

After all components were tuned, calibration was finalized by adjusting all components together until the best model-to-flow data “fit” was achieved. Reduced emphasis was placed on periods with unreliable or inconsistent diurnal wastewater flow patterns (such as holidays). Figure 8-5 presents a plot of simulated flow (black) versus measured flow (red). Rainfall (purple) is included on the reverse second Y-axis for reference. Also included for reference are the wet weather I/I components: fast response (magenta), rapid infiltration (green), and slow infiltration (blue). Plots showing the match between simulated and measured flow for the entire calibration of each pilot and control basin are included in Appendix F.

The calibration process was based on the monitored flow data. The confidence in final model parameter combinations decreased when large amounts of data were missing or not collected. See Appendix F for a qualitative assessment of model confidence and final reduction results.

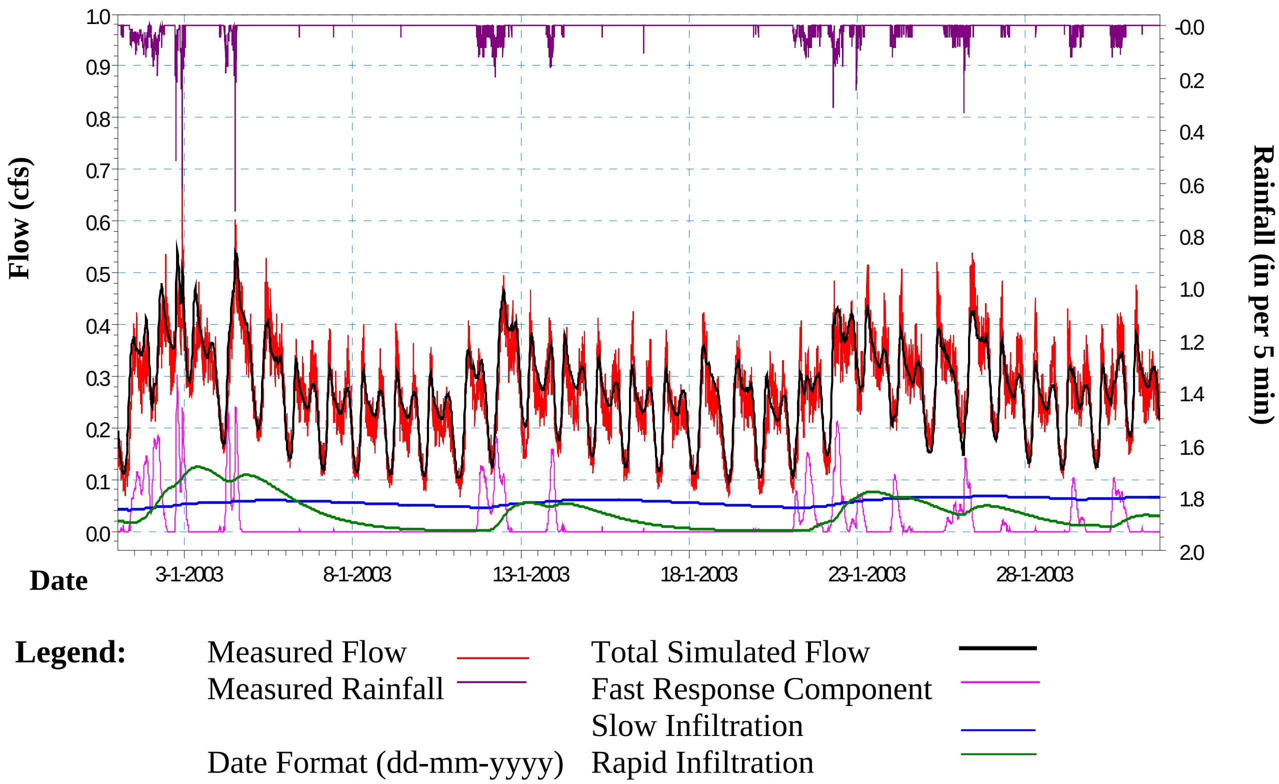


Figure 8-5. Model Calibration Example

8.5.4 Estimated 20-Year Peak Flows

King County has adopted a 20-year flow capacity standard for conveyance facilities that transport wastewater from local agencies to County treatment plants. This means the facilities must have capacity for flows of a magnitude that can be expected on an average of once every 20 years (20-year return period). This corresponds to a 5-percent chance of such flows or higher occurring in any given year. To maintain consistency with King County capacity standards, the difference in the 20-year flow established for pre-rehabilitation versus post-rehabilitation was used to estimate rehabilitation effectiveness.

To estimate the benefits of I/I reduction, it is also necessary to estimate reduction in the 20-year flow achieved through system rehabilitation. It is unlikely that an event as infrequent as the 20-year flow will be measured during a short monitoring period; therefore, alternative methods were developed to estimate the 20-year flow. Many traditional methods, such as the "design storm approach," equate rainfall probability to flow probability. These methods become unreliable when flow of a given magnitude can result from a range of rainfall events. As antecedent conditions become more significant in determining flow response, it becomes increasingly difficult to correlate flow to a single rainfall event. The design storm approach lacks the ability to account for varying geographic coverage, antecedent conditions, or impacts from successive rainfall events, all of which are common in this region. An additional consideration is the sensitivity of flows resulting from rainfall received over successive days, weeks, or even months.

The method used to estimate the 20-year flow for each basin consisted of conducting an extended simulation and performing a frequency analysis on the simulated flows. Through calibration of the continuous simulation model to measured flows, the parameters describing each basin were adjusted to represent the processes that transform rainfall to infiltration and inflow. The model can then be used to simulate flow response from a long-term rainfall time series that includes large, infrequent rainfall events. By simulating a continuous, long-term period, this approach accounts for the effects of antecedent conditions.

8.5.4.1 20-Year I/I Flow Estimation Procedure

After the hydrologic model for each basin was calibrated, it was simulated with a 60-year extended time series (ETS) of precipitation as input. The ETS were developed to facilitate application of continuous simulation hydrology despite variability of mean annual precipitation and infrequent rainfall event volumes throughout the study area. The ETS applicable to the King County study area were developed by adjusting the 60-year SeaTac rainfall record to match the storm statistics of the time series records at over 50 precipitation gauges located in the lowlands of western Washington. More specifically, a series of statistical scaling functions were used rather than a single scaling factor. The scaling functions provide for scaling rainfall amounts at the 2-hour, 6-hour, 24-hour, 72-hour, 10-day, 30-day, 90-day, and annual durations.

The 60-year simulation produces a time series of flows at the basin outlet. This 60-year flow time series can be used to determine flow frequency, which includes estimating the 20-year peak I/I flow from each model basin. The procedure for estimating the 20-year peak I/I flow can be summarized in the following steps:

1. Develop and calibrate a basin model using rainfall and flow data measured in the basin.
2. Simulate flow response with the calibrated model using the 60-year extended time series (ETS) of precipitation as input.
3. Extract, rank, and plot the simulated peak I/I flows.
4. Estimate the 20-year I/I flow from the plot of peak flows.

The ETS simulation produces 60 years of simulated flows at the basin outlet. From this information, a plot can be made of peak flow magnitude versus return period such as the one shown in Figure 8-6. A best-fit curve was used to interpolate between the plotted points with a return period greater than 1 year. The estimated 20-year flow was determined by selecting the flow from the plotted best-fit curve with a return period of 20 years. See Appendix F for the plots of the frequency analysis (regression) curves for the modeled basins.

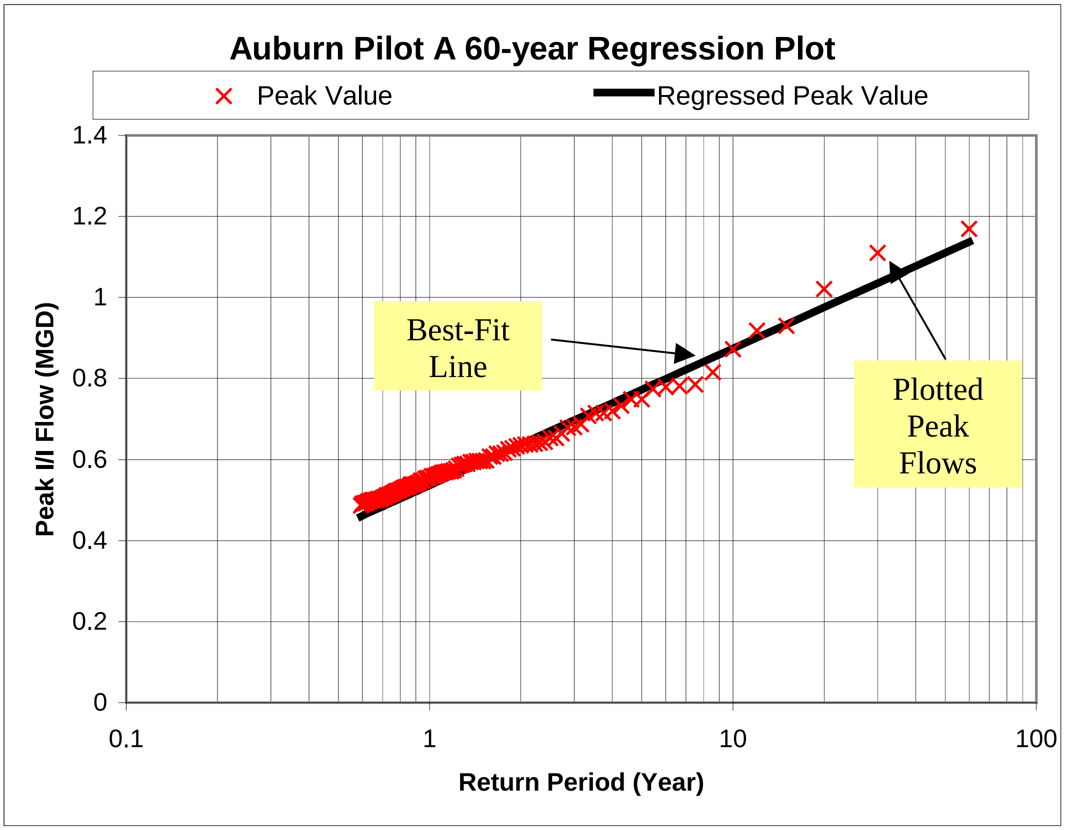


Figure 8-6. Assigning Return Intervals to Peak Simulated Flows

This process relies on several key assumptions. The ETS were derived using the SeaTac rainfall record, which is the longest continuous record of rainfall data in the eastern Puget Sound lowlands. It was assumed to be representative of rainfall patterns likely to occur in the service area, after adjustments were made to account for annual and peak rainfall differences throughout the region. Another key assumption is that a calibrated model can simulate flow response from any rainfall time series. Representation of multiple flow components and calibration to varied conditions provides a reasonable basis for such an extrapolation assuming that the events calibrated to are large enough to be able to project out to the 20-year event. See Appendix F for a model confidence table.

8.5.4.2 Pre-Rehabilitation 20-Year Flow Estimates

Table 8-3 presents the pre-rehabilitation 20-year peak flow estimates for each control and pilot basin using the approach and methodology described in previous sections. Frequency analysis was conducted independently on four flow components of interest: total flow, total I/I (total flow minus diurnal wastewater flow), fast response, and slow response (the sum of slow and rapid infiltration). It should be reiterated that the flows presented in Table 8-3 were estimated using flow modeling of the pilot and control basins; thus, they differ from the flows used for pilot project selection, which were derived from measured flows. For each flow component included in Table 8-3, the 20-year flow is presented in million gallons per day (mgd) and in gallons per acre per day (gpad). These 20-year flow values estimated for pre-rehabilitation conditions provide the initial basis for determining I/I reduction.

Table 8-3. 20-Year Peak Flow Estimates for Pre-Rehabilitation Conditions

Basin Name	Total Flow		Total I/I		Fast Response[1]		Slow Response[1]	
	(mgd)[a]	(gpad)[b]	(mgd)	(gpad)	(mgd)	(gpad)	(mgd)	(gpad)
Auburn Pilot A	1.1	9,900	1.0	8,900	0.5	4,500	0.7	6,400
Auburn Pilot B	1.2	31,400	1.1	29,100	0.5	12,800	0.7	20,100
Brier Control	0.5	4,600	0.5	4,100	0.2	2,100	0.3	2,700
Brier Pilot	1.0	10,700	0.9	10,100	0.1	700	0.9	9,800
Coal Creek Control	1.2	12,000	1.1	11,000	0.4	3,700	0.8	8,500
Coal Creek Pilot	1.2	8,000	1.1	7,400	0.4	2,500	0.8	5,700
Kent Control	0.1	4,700	0.1	4,000	0.0	700	0.1	3,300
Kent Pilot	0.6	14,000	0.5	12,700	0.0	1,000	0.5	12,000
Kirkland Control	0.8	17,900	0.7	15,200	0.4	9,300	0.4	8,800
Kirkland Pilot	0.9	11,700	0.9	11,000	0.4	5,200	0.6	7,200
Lake Forest Park Control	2.7	14,700	2.6	13,900	1.0	5,300	2.2	12,000
Lake Forest Park Pilot	3.2	22,900	3.2	22,500	1.0	7,000	2.5	17,900
Mercer Island Control	0.4	12,100	0.4	11,400	0.1	3,900	0.3	9,200
Mercer Island Pilot	0.9	8,900	0.9	8,200	0.5	4,800	0.6	5,500
Northshore Control	0.7	6,300	0.6	5,800	0.2	1,600	0.6	5,200
Northshore Pilot	1.0	6,900	1.0	6,600	0.3	2,200	0.8	5,200
Redmond Control	0.2	3,200	0.1	1,100	0.0	400	0.0	800
Redmond Pilot A	0.2	2,600	0.1	1,000	0.0	300	0.0	600
Redmond Pilot B	0.6	12,800	0.5	11,000	0.0	400	0.5	10,700
Ronald Control	1.1	12,100	1.0	11,100	0.5	5,500	0.8	8,400
Ronald Pilot	1.7	18,900	1.7	18,200	0.3	2,800	1.5	16,400
Skyway Control	1.7	44,500	1.7	43,800	0.7	18,000	1.4	36,600
Skyway Pilot[2]	2.7-3.1	58,700-67,600	2.7-3.1	57,700-66,700	0.4-0.8	8,700-17,300	2.5-2.7	54,000-59,500
Val Vue Control	0.9	4,400	0.8	3,900	0.4	2,100	0.6	3,200
Val Vue Pilot	0.3	4,400	0.3	3,800	0.2	2,700	0.2	2,600

[a] million gallons per day [b] gallons per acre per day

1 - The fast and slow response values do not sum to the total I/I. The tool developed to estimate the 20-year peak flows treats each of the responses independently. The fast response peak may not coincide with the slow response peak.

2 - Two equivalent calibrations using different sets of parameters were developed for the Skyway pilot; therefore, ranges of rates were identified.

8.6 I/I Reduction

8.6.1 I/I Reduction Estimated with Modeling

Modeling analysis was used to estimate I/I reduction achieved in each pilot project basin through system rehabilitation. The modeling approach tasks are presented in Figure 8-7. Pre-rehabilitation I/I quantities for each pilot and control basin were determined with models calibrated to available measured flow and rainfall data collected prior to rehabilitation. The pre-rehabilitation 20-year peak I/I flow contributed by each basin was then determined through frequency analysis of simulated flows generated from 60-year ETS simulations. Pre-rehabilitation 20-year peak I/I estimates are presented in Table 8-3.

The first step in the process of quantifying I/I reduction was to simulate the post-rehabilitation period using the models calibrated to pre-rehabilitation conditions. In essence, the pre-rehabilitation models were used to simulate flows expected from each basin if rehabilitation improvements were not constructed. If the simulated flows from the pre-rehabilitation model were higher than the flows measured during the post-rehabilitation period, then it could be concluded that the rehabilitation improvements resulted in decreased I/I. Figure 8-8 illustrates an example in which I/I was reduced with rehabilitation. The result from the model calibrated to pre-rehabilitation conditions simulates higher flows (gray) during the post-rehabilitation period than the measured flows (red).

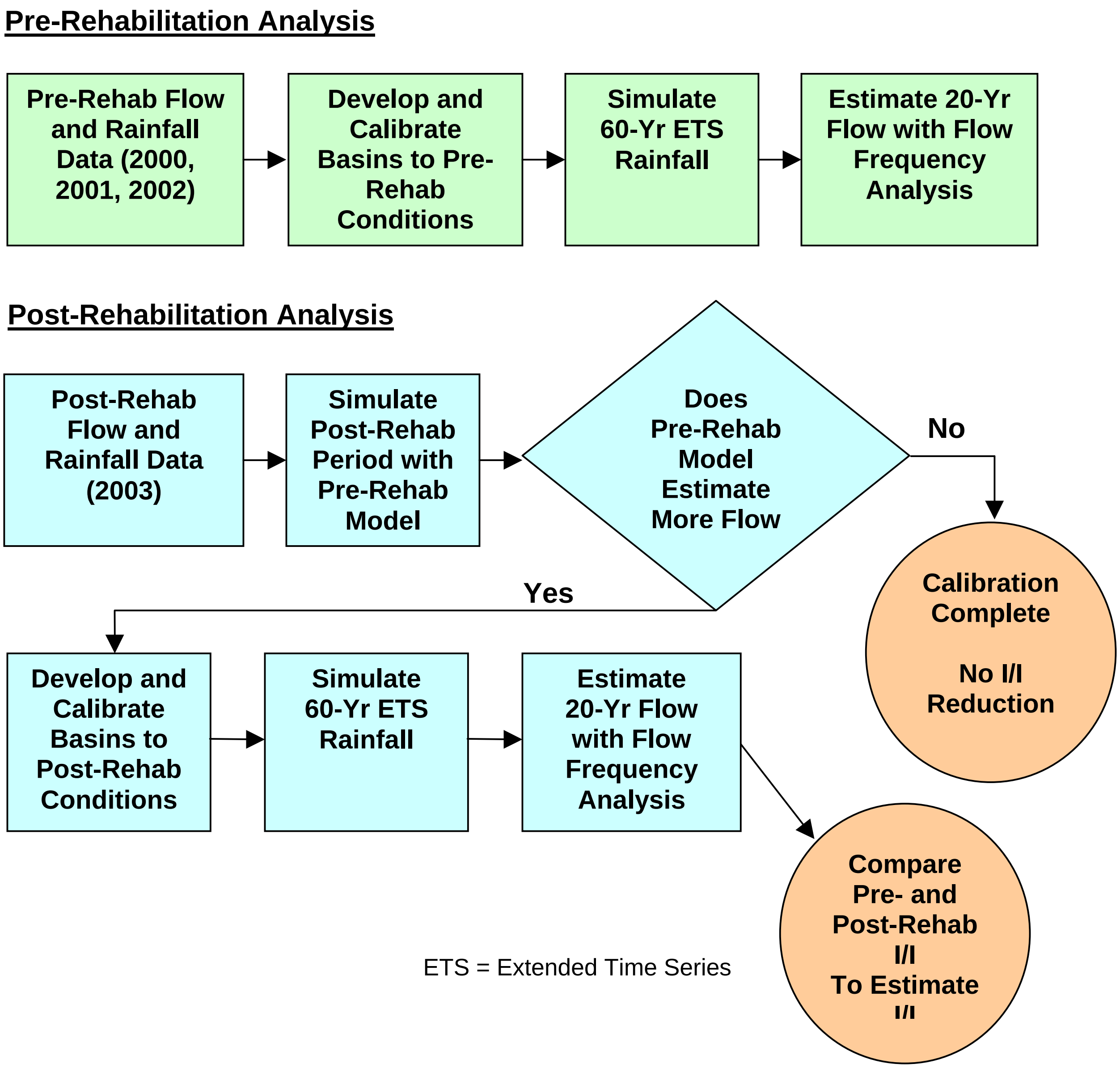


Figure 8-7. Modeling Approach for Estimating I/I Reduction

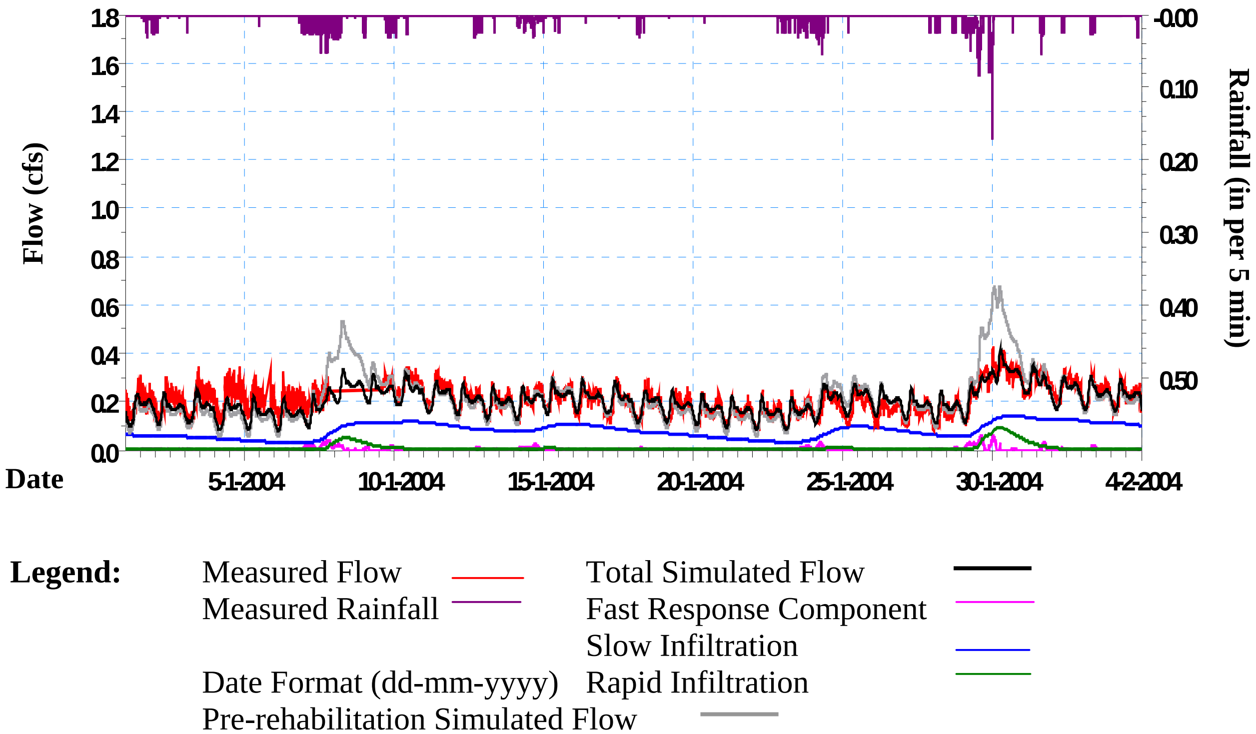


Figure 8-8. Post-Rehabilitation Flow Data with Model Calibrated to Pre- and Post-Rehabilitation Conditions

For most pilot project basins, there was clearly a reduction in I/I; however, for some basins, I/I reduction was not apparent. In cases where the model calibrated to pre-rehabilitation conditions simulated flows equal to or less than the measured flow during the post-rehabilitation period, it was concluded that I/I was not reduced by rehabilitation improvements.

For basins where I/I was reduced, additional modeling tasks were required to quantify the amount of I/I reduction. The next step was to recalibrate the MOUSE model to match post-rehabilitation measured flows. The model calibration process is described in Section 8.5.3. After calibrating to post-rehabilitation conditions, the flow frequency analysis was conducted to estimate post-rehabilitation 20-year peak I/I flow. I/I reduction was estimated by comparing the 20-year peak I/I flow before and after rehabilitation improvements were constructed (see Figure 8-9 for an example). I/I reduction estimates for each pilot basin are presented in Table 8-4. Plots showing the simulated and measured flow for each pilot and control basin during the post-rehabilitation period are included in Appendix F.

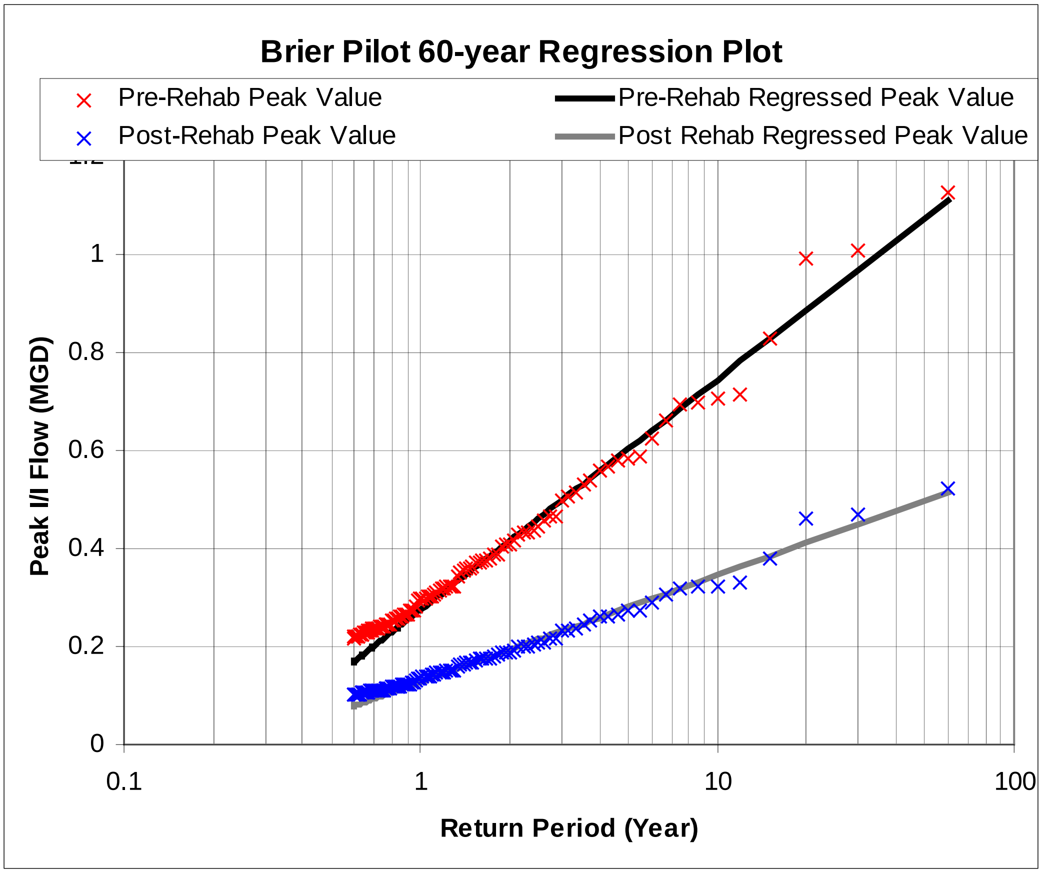


Figure 8-9. Flow Frequency Comparison of Pre-Rehabilitation and Post-Rehabilitation Model Results

Table 8-4. Pilot Project I/I Reduction Estimated from Model Results

Basin Name	Mains	Manholes (MH)	Laterals (L)	Side Sewers (SS)	% Improved[1]	Total I/I Pre-Rehab (gpad)	Total I/I Post-Rehab (gpad)	Total I/I Reduction %	Fast Response Reduction %	Slow Response Reduction %
Auburn Pilot A	•	•	•	•	11 of Mains	8,900	8,900	NAR[2]	NAR[2]	NAR[2]
Auburn Pilot B		•			19 of MH	29,100	29,100	NAR	NAR	NAR
Brier Pilot	•	•			23 of Mains	10,100	5,000	50	0	55
Coal Creek Pilot		•			52 of MH	7,400	7,400	NAR	NAR	NAR
Kent Pilot[3]			•	•	100 of L and SS	12,700	2,400-3,700	71-81	0	75-85
Kirkland Pilot	•	•	•		25 of Mains	11,000	7,900	28	41	19
Lake Forest Park Pilot	•	•			35 of Mains	22,500	7,100	69	55	71
Mercer Island Pilot	•				70 of Mains	8,200	5,200	37	50	26
Northshore Pilot		•			64 of MH	6,600	5,100	23	49	17
Redmond Pilot A	•	•	•		36 of Mains	1,000	1,000	NAR	NAR	NAR
Redmond Pilot B	•	•			8 of Mains	11,000	11,000	NAR	NAR	NAR
Ronald Pilot			•	•	72 of L and SS	18,200	4,800	74	60	74
Skyway Pilot[3]	•	•	•	•	100 of System	58,700-67,600	7,800-8,900	86	74-85	88-90
Val Vue Pilot		•			45 of MH	3,800	3,800	NAR	NAR	NAR

1 " % Improved" refers to the amount of rehabilitation improvement completed for identified elements of the sewer system. For example, for Coal Creek, the 52% value indicates that 52% of the manholes in the pilot basin were improved. "% Improved" for mains is quantified based on length of sewer main improved. Manholes, laterals, and side sewers are quantified based on the number of each element improved relative to the total number present in the pilot basin (i.e., laterals and side sewers were not quantified based on "% of length improved").

2 No Apparent Reduction (NAR)

3 Two equivalent calibrations using different sets of parameters were developed for Skyway and Kent and therefore a range of rates were identified

8.6.2 I/I Reduction Estimated Using Control Basins

An alternative to estimating I/I reduction with modeling is to calculate I/I reduction using measured flows from the pre-rehabilitation and post-rehabilitation monitoring periods. It would not be appropriate to simply compare measured flows in the pilot basins from pre-rehabilitation to post-rehabilitation conditions because the rainfall events and antecedent conditions throughout each monitoring period are unique. However, the measured flows from the control basins can be compared with the pilot basins for the two different monitoring periods. Although the two monitoring periods have different rainfall signatures and antecedent conditions, the relative difference between the pilot and control basins should be the same from period to period. If the relative difference changes from one monitoring period to another, then a reduction can be quantified. Comparing pre-rehabilitation and post-rehabilitation measured flow data in each pilot basin and corresponding control basin can determine the I/I reduction in each pilot basin.

The general approach to determine I/I reduction was to compare the pilot versus control ratio computed for individual rainfall events before and after rehabilitation improvements. Percent reductions were calculated for peak values and 48-hour volume (from the start of a given storm event). A more detailed description of the task sequence is provided below:

1. Subtract the diurnal wastewater flow during selected storms from the pre-rehabilitation data for both the pilot and control basins.
2. Identify and record peak total I/I and 48-hour total I/I volume during the selected storms (for both the pilot and control basins) from the pre-rehabilitation data.
3. Calculate the average pilot versus control ratio for both peak total I/I and 48-hour total I/I volume.
4. Calculate the projected I/I from the pilot basin using the average of the calculated ratios and flow data from the post-rehabilitation control basin. (The projected values represent what the peak total I/I and 48-hour total I/I volume would have been had the pilot basin not been rehabilitated.)
5. Compare the projected values (for the post-rehabilitation pilot basin) with the post-rehabilitation measured values (for the same basin) and the I/I rehabilitation. Calculate effectiveness as percent reduction.

I/I reduction estimates derived from the measured flow data are presented in Table 8-5.

Table 8-5. Pilot Project I/I Reduction Estimated from Measured Flow

Site Name	Peak Flow	Modeled 20-year Total I/I (See Table 8-4)	48-Hour Volume
	% Reduction	% Reduction	% Reduction
Auburn Pilot A	Not Applicable (NA)	No Apparent Reduction (NAR)	NA
Auburn Pilot B	NA	NAR	NA
Brier Pilot	36	50	40
Coal Creek Pilot	39	NAR	41
Kent Pilot	60	71-81	56
Kirkland Pilot	28	28	18
Lake Forest Park Pilot	65	69	61
Mercer Island Pilot	44	37	21
Northshore Pilot	82	23	82
Redmond Pilot A	NA	NAR	NA
Redmond Pilot B	NA	NAR	NA
Ronald Pilot	57	74	17
Skyway Pilot	77	86	85
Val Vue Pilot	NA	NAR	NA

1 The NA designation differs from the NAR designation in that the analysis could not be done for anything with a NA designation. The level of reduction is unknown.
2 The peak-to-peak ratio analysis was done on peaks much smaller than the 20-year event and does not represent a 20-year reduction.

While this approach may be used to quantify the I/I reduction independently of the modeling results, some issues became apparent as the data was analyzed. The flow data based approach relies on peak flow ratios (or flow volume ratios) and the presence of data gaps in some cases severely limited an already small sample of data points. In theory, this approach requires a reasonably large data set to generate statistically acceptable ratios.

Another issue was inconsistency in the pilot versus control ratio among measured storms. This relatively simple approach does not distinguish between different types of I/I flow. It also does not represent the non-linear nature of I/I response to rainfall events of various sizes or with varying antecedent conditions. During the 2002/2003 pre-rehabilitation monitoring period, there was a limited number of large storm events from which to generate ratios. The small number of storm events led to a relatively high standard deviation in the statistical analysis of the pilot versus control ratios. Also, the limited number of large storm events during the post-rehabilitation monitoring period did not allow generation of many data points that would show consistency in percent reduction or effectiveness of the rehabilitation.

Determining peak I/I flows cannot be achieved when pump stations influence flow monitoring sites. This was the case for Val Vue. The Val Vue pilot basin shows negative 48-hour I/I volume reduction and 70 to 80 percent peak I/I reduction when pre- and post- rehabilitation data are compared. The percent reduction analysis could not be applied to Val Vue data.

The percent reduction analysis also was not performed for the Auburn and Redmond pilot basins. A control basin was unavailable at the Auburn site for comparison against the Auburn Pilot Basin A. The Redmond basin was missing too much data during the pre-rehabilitation monitoring period for the analysis to give reasonable results.

8.7 Rehabilitation Effectiveness

Section 8.6 presented the approach to quantifying I/I reduction and the estimated I/I reduction achieved in each pilot basin. Estimating I/I reduction in each pilot basin was a relatively direct and quantitative process. Comparing results obtained in different pilot basins to determine the rehabilitation effectiveness of different techniques was less direct. Because of the small sample size, it was necessary to consider many characteristics of each individual pilot basin to put the I/I reduction quantities in perspective. Section 8.7 presents pertinent information about I/I reduction achieved in each pilot basin.

8.7.1 Auburn Pilot Basin A

In Auburn Pilot Basin A, few defects were identified in the public sewer system. The Sewer System Evaluation Survey (SSES) investigations of the public system identified very few defects in the sewer mains and manholes. Several of the laterals and side sewers in the pilot basin were inspected and very few defects were identified. However, defects were identified in the private sewer of the Auburn Adventist Academy. As a result, the rehabilitation effort focused on this private sewer system. In terms of the total length of sewer main in the pilot basin, approximately 11 percent of the system was rehabilitated. While only a small percentage of the basin was rehabilitated, the improvements targeted almost all the identified defects in the basin.

Flow measurement in Auburn Pilot Basin A was more challenging than in other pilot and control basins. To isolate the flow from Pilot Basin A, flow from an upstream pump station (Auburn Subtraction meter) was subtracted from flow measured at the Pilot A meter. As a result, it was difficult to quantify the net flow from Pilot Basin A. Model results did not indicate any I/I reduction in Pilot Basin A. In this instance, it is likely that the challenging flow monitoring conditions would have allowed recognition of only dramatic I/I reduction (greater than 75-percent reduction).

8.7.2 Auburn Pilot Basin B

Auburn Pilot Basin B was proposed after field investigations established that several manholes in the basin were prone to surface inundation. The completed improvements targeted these potential inflow sources. To isolate the flow from Pilot Basin B, flow from the upstream Pilot Basin A was subtracted from flow measured at the Pilot B meter. The pump station influence from the Auburn Subtraction meter (see Section 8.7.1) was present at both the Pilot A and Pilot B meters. As a result, it was difficult to quantify the net flow from Pilot Basin B.

Model results indicated the presence of significant I/I in Pilot Basin B in the form of both fast response and rapid infiltration. Model results did not indicate any I/I reduction in Pilot Basin B. The presence of multiple private sewer systems that were not inspected and substantial I/I not attributed to fast response suggest that the Pilot B improvements targeted only a fraction of the potential I/I sources in the basin. In this instance, it is likely that the challenging flow monitoring conditions would have allowed recognition of only dramatic I/I reduction (greater than 75-percent reduction).

8.7.3 Brier Pilot Basin

In the Brier Pilot Basin, rehabilitation improvements focused on mains and manholes. Approximately 23 percent of the system was rehabilitated in terms of the total length of sewer mains in the basin. Side sewers and laterals were not inspected prior to construction. Reduction in the 20-year peak I/I was estimated at 50 percent based on model results.

8.7.4 Coal Creek Pilot Basin

The Coal Creek Pilot Basin was one of three projects that focused solely on repair of manholes. Improvements were based on visual inspection of manholes to identify sources of inflow, infiltration, and rapid infiltration. Approximately 52 percent of the manholes in the pilot basin were rehabilitated. Model results did not indicate any I/I reduction resulting from the completed improvements.

8.7.5 Kent Pilot Basins A and B

Rehabilitation improvements in the Kent Pilot Basin A and Pilot Basin B focused on side sewers and laterals. The SSES showed some defects in mains and manholes, but few located in the pilot basin. Due to the proximity of a downstream pump station, monitoring of the pilot area was required at two locations. Because both pilot basins were small and appeared to be similar, they were considered together as one pilot basin in the modeling analysis. Nearly 100 percent of the side sewers and laterals were rehabilitated. Reduction in the 20-year peak I/I was estimated at 71 to 81 percent based on model results.

8.7.6 Kirkland Pilot Basin

In the Kirkland Pilot Basin, SSES results revealed defects in mains, manholes, laterals, side sewers, and in several direct inflow sources (e.g., foundation drains, downspouts, roof drains). Kirkland was originally selected as a pilot basin where side sewers would be included as part of the rehabilitation. However, due to complications, side sewers were excluded. The completed improvements consisted of mains, manholes, and laterals. Approximately 25 percent of the system was rehabilitated in terms of the total length of sewer mains in the pilot basin. Unlike in other pilot basins, the construction budget determined the amount of rehabilitation work in the Kirkland Pilot Basin. In the other pilot basins, the lack of improvements in a fraction of the system was a result of the absence of defects in those areas. Reduction in the 20-year peak I/I was estimated at 28 percent based on model results.

8.7.7 Lake Forest Park Pilot Basin

Improvements in the Lake Forest Park Pilot Basin focused on mains and manholes. Approximately 35 percent of the system was rehabilitated in terms of the total length of sewer mains in the basin. Side sewers and laterals were not inspected prior to construction. Reduction in the 20-year peak I/I was estimated at 69 percent based on model results.

8.7.8 Mercer Island Pilot Basin

In the Mercer Island Pilot Basin, significant defects were found by the SSES within the mains and service connections. A few inflow sources were found by positive smoke tests. Given the age of the system, there may also have been defects in laterals and side sewers, but these components were not inspected prior to construction. Designers chose to focus solely on mains and service connections in this pilot basin, thereby testing removal effectiveness based on those system components. Approximately 70 percent of the system was rehabilitated in terms of the total length of sewer mains in the basin. Reduction in the 20-year peak I/I was estimated at 37 percent based on model results.

Flow measurement in the Mercer Island Pilot Basin was challenging. To isolate the flow from the pilot basin, flow from the upstream control basin was subtracted from flow measured at the Mercer Island Pilot Basin meter. In addition, it was discovered that hydraulics downstream of the meter location inhibited the ability to accurately measure velocity over the full range of flow conditions. In order to utilize measured flow at the Mercer Island Pilot Basin meter, a correction to the raw measured values was required for periods of high flow (see Appendix D).

8.7.9 Northshore Pilot Basin

The Northshore Pilot Basin was one of three projects that focused solely on repair of manholes. Improvements were based on visual inspection of manholes to identify sources of inflow, infiltration, and rapid infiltration. Approximately 64 percent of the manholes in the pilot basin were rehabilitated. Reduction in the 20-year peak I/I was estimated at 23 percent based on model results. One significant direct inflow source was also eliminated, contributing an unknown proportion of the 23-percent reduction estimate.

8.7.10 Redmond Pilot Basin A

Within the Redmond mini-basin, the SSES identified defects in all portions of the collection system. However, due to complications during the formulation and design of the Redmond Pilot, a portion of the selected mini-basin was designated as Redmond Pilot A. Rehabilitation improvements focused on mains, manholes, and laterals. Approximately 36 percent of the system was rehabilitated in terms of the total length of sewer mains in Pilot Basin A. Model results did not indicate any I/I reduction resulting from the improvements. The good quality flow data for this basin did not limit recognition of I/I reduction. Model results estimated the 20-year peak I/I to be just 850 gpad, which is comparable to the least amount of I/I in King County wastewater service area mini-basins.

8.7.11 Redmond Pilot Basin B

As previously mentioned, the content of the pilot project improvements in Redmond were modified during design. Significant defects were identified in the downstream portion of the Redmond mini-basin. Rehabilitation improvements in the Redmond Pilot Basin B consisted of selected spot repairs. Less than 5 percent of the system was rehabilitated in terms of the total length of sewer mains in Pilot Basin B. To isolate the flow for Pilot Basin B, flow from both the upstream control basin and Pilot Basin A were subtracted from flow measured at the Pilot Basin B meter.

The most challenging aspect of analyzing this pilot basin was the apparent link between flows in the adjacent Sammamish River and I/I flows in Pilot Basin B. Model results did not indicate any I/I reduction resulting from the completed improvements.

8.7.12 Ronald Pilot Basin

Flow monitoring indicated that this basin had significant I/I--approximately 11,000 gpad. Table 8-3 shows total flow for the Ronald pilot basin to be 18,000 gpad. However, previous Ronald Wastewater District (RWD) sanitary sewer evaluation work in this basin (sewer main and manhole inspection and smoke testing) revealed relatively few faults. Only 7 sewer main faults were noted, and about 10 faults that could allow I/I were observed on private property. With so few defects in the sewer main, the most likely source of I/I must be the side sewers and laterals. Those components were the focus for the pilot project work. Approximately 72 percent of side sewers and laterals were rehabilitated. Reduction in the 20-year peak I/I was estimated at 74 percent based on model results.

8.7.13 Skyway Pilot Basin

In Skyway, the pilot project consisted of full system rehabilitation (mains, manholes, side sewers, and laterals). Within the entire pilot basin, all portions of the collection system were replaced from the house to the lateral connection at the main. With a pre-rehabilitation 20-year peak I/I between 58,700 and 67,600 gpad, the Skyway pilot basin had the highest I/I in the King County wastewater service area. Nearly 100 percent of the system was rehabilitated in terms of the total length of sewer mains in the pilot basin. Reduction in the 20-year peak I/I was estimated at 87 percent based on model results.

8.7.14 Val Vue Pilot Basin

The Val Vue pilot basin was one of three projects that focused solely on repair of manholes. Improvements were based on visual inspection of manholes to identify sources of inflow, infiltration, and rapid infiltration. Approximately 45 percent of the manholes in the pilot basin were rehabilitated. Model results did not indicate any I/I reduction resulting from the improvements. In this instance, it is likely that the challenging flow monitoring conditions, influenced by nearby pump stations, would have allowed recognition of only dramatic I/I reduction (greater than 75-percent reduction).